HALDEMAN, MICHAEL EDWARD, D.M.A. Stroke Velocity in Two-Mallet Marimba Performance. (2008)
Directed by Cort A. McClaren. 66 pp.

The purpose of this study was to measure and report stroke velocity in two-mallet marimba performance using a tri-axial accelerometer module and *LabView 5.1* data collection and display software. A review of keyboard percussion instrument pedagogy materials and a review of previous research completed in this area of study revealed a lack of information dealing with the ability to quantify stroke velocity executed by a percussionist when playing keyboard percussion instruments.

Pedagogical materials addressing keyboard percussion instruments were reviewed and three previous scholarly studies aided in the design of this study. Using a tri-axial accelerometer, a low velocity and high velocity piston stroke were measured, as well as three variations of a piston stroke as outlined by Leigh Howard Stevens in his book *Method of Movement for Marimba.* Stroke velocity in selected two-mallet marimba excerpts were also measured.

Data was organized by specified stroke motions and excerpts. Line graphs were used to indicate stroke velocity values calculated using a mathematical formula that converted the x, y, and z axes of acceleration values into one composite stroke velocity measurement.

The conclusion of this study indicates that stroke velocity can be quantified adhering to the outlined methods found in this research design. Further studies are needed to determine any relationship between stroke velocity and sound quality.

STROKE VELOCITY IN TWO-MALLET

MARIMBA PERFORMANCE

by

Michael Edward Haldeman

A Dissertation Submitted to
the Faculty of the Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Musical Arts

Greensboro
2008

Approved by

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Committee Chair

To my parents…

Who always encouraged and allowed me to try something…

at least once,

Attended every soccer game, scout meeting, drum lesson, and band concert…

even if they didn't really want to,

Had the knowledge to put their two cents in…

and the wisdom to let me be on my own.

To my brother…

Who from time to time had to remind me it isn't

all about a big house and a nice car…

You are the best friend a brother could ever have.

APPROVAL PAGE

This dissertation has been approved by the following committee of the

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ACKNOWLEDGMENTS

I would like to extend my deepest gratitude to my committee chair, Dr. Cort McClaren. Over the five years that I have been his student, he has cultivated my ability to be an influential teacher, a better performer, a deep thinker, and most importantly a better person. His knowledge, intellect, and ability to inspire is infectious.

A sincere thanks to my committee members, Dr. Dennis Askew, Dr. Scott Rawls, and Dr. Welborn Young. Their guidance and knowledge has influenced me both within my research and outside of higher academia. I aspire to be as influential to my students as they were to me.

An enormous amount of gratitude to Dr. Randy Schmitz for his help with "crunching" the data. Without his help this study would not have been possible. Additional thanks to Christina Palermo for her aid in collecting data during this study, and thanks to Jessica Bays for her help in proofreading and grammatically aiding in the completion of this document.

Thank you to my family and friends for their love, support, and encouragement. Thank you to my parents, John and Lois Haldeman, for their unwavering support throughout my educational aspirations and career goals. They taught me to function with a strong work ethic, to believe in myself, and to know when to take a break along the way. Thank you to my brother Matthew, who always said just the right words to

put things into perspective when my focus was a bit off. Thank you to my grandparents, Alyou and Mae Bredbenner, and William and Mary Haldeman. They are a constant reminder to me that knowledge is learned through books, but wisdom is learned through experience. I miss you Pop-pop B.

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CHAPTER I

INTRODUCTION

Percussionists produce sound by striking an object and causing it to vibrate. The object used by a percussionist comes in many forms such as a drumhead, marimba bar, vibraphone bar, suspended cymbal, or timpani head. The specific physical movement of a percussionist's lower body, upper body, arms, wrists, and hands determine the type of sound produced. An understanding of these physical movements will ultimately enable a percussionist to produce multiple timbres and control sound quality while performing.

One of the most widely accepted factors that affect timbre and sound quality is striking motion. Cort McClaren, in his book *The Book of Percussion Pedagogy: A Step-By-Step Approach for Teachers and Performers*, defines striking motion as the method of "hitting" an instrument.[1] The manner in which a percussionist strikes an instrument determines the quality of sound produced.[2] He further states that piston motion is recommended for all percussion performance. Piston motion will provide the most

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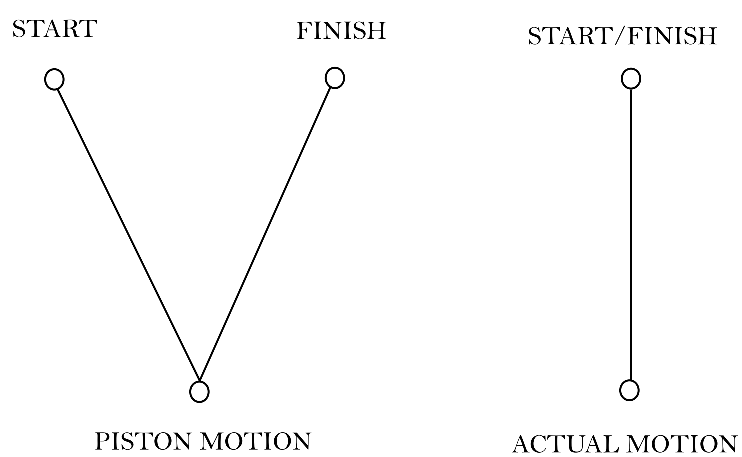
[1] Cort McClaren, *The Book of Percussion Pedagogy: A Step-By-Step Approach for Teachers and Performers*, 2nd ed. (Greensboro: C. Alan Publications, 2006), 1.

[2] Ibid., 6.

efficient movement for all percussion instruments.[3] Figure 1 below illustrates the path of travel of a stroke with piston motion, also called the piston stroke.

Figure 1: Piston Motion[4]



Piston motion is a single motion that starts and ends at a predetermined height.[5] The V-shape of this movement, as illustrated to the left, does not indicate a glancing blow to the instrument. This figure represents a single motion in which the stick travels from a predetermined height down to the instrument and returns to the original position or another predetermined height.[6]

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[3] Ibid.
[4] Ibid., 5.
[5] Ibid.
[6] Leigh Howard Stevens, *Method of Movement for Marimba*, 4th ed. (Leigh Howard Stevens, 1997), 5.

The information involving piston motion is intended to provide a general knowledge of one widely accepted method of striking percussion instruments. In this study, piston motion was applied and manipulated during data collection. Subsequent reference to piston motion or the piston stroke is assumed to apply to a marimba unless otherwise specified.

In his book, *Method of Movement for Marimba*, Leigh Howard Stevens states that, "although variation in terminology exists, the two most often recommended stroking methods are: (1) the stroke with preparation (up – down), and (2) the stroke with lift (down – up)".[7] He further recommends the use of piston or cyclic motion while playing the marimba.[8]

> There is nothing new or unusual about the piston stroke. Even players who advocate the use of preparation or lift routinely use a piston style stroke when playing fast passages. (There is no time between rapid stroke repetitions for preparation or lift.) Rather than have a "slow tempo stroke" and a "fast tempo stroke", this author strongly recommends that the marimbist use the same piston stroking method in practice and slow tempi as in performance and fast tempi.[9]

In his publication, Stevens further advocates the use of piston motion even in an instance where a small preparatory stroke is used. In addition, he states that

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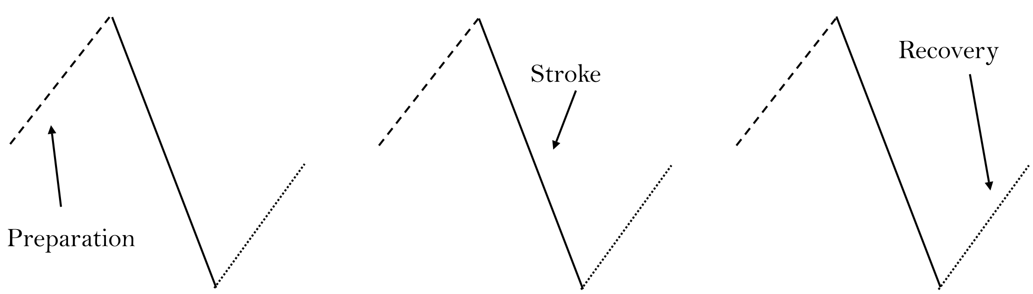
[7] Ibid., 16.
[8] Ibid.
[9] Ibid.

consecutively executed strokes at moderate to fast tempi result in multiple instances of piston strokes due to the inherent need for stroke efficiency.[10]

Chapter IX of Part 1 in Stevens' book addresses the path of travel of the piston stroke with several commonly misused variations. In Figures 2, 3, and 4 below, a series of strokes and variations are illustrated. A solid line represents the actual stroke, dotted lines represent recovery of a stroke, and dashed lines represent preparation before the stroke.

Figure 2: Stroke with Preparation[11]



[10] Ibid.
[11] Ibid.

Figure 3: Stroke with Lift[12]

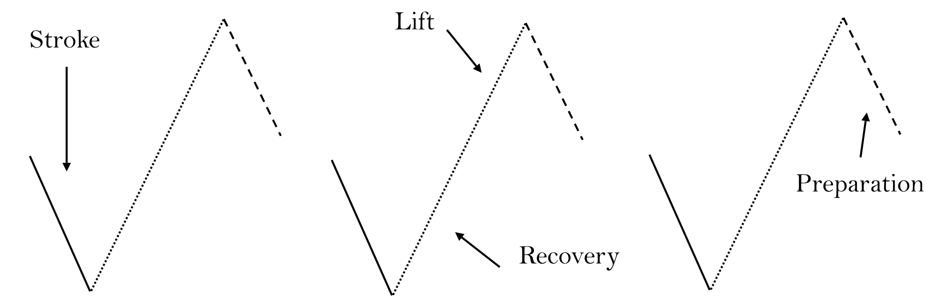
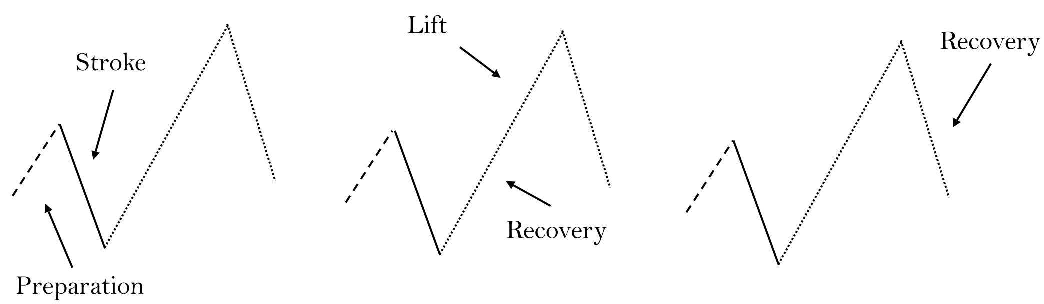


Figure 4: Stroke with Preparation and Lift[13]



According to Stevens, the stroke with preparation, the stroke with lift, and the stroke with preparation and lift contain motion that is unnecessary to create sound on percussion instruments. To further clarify, Stevens extracts one stroke from Figures 2, 3, and 4, assigns labels to these strokes, and identifies the unnecessary motions in brackets. The individual strokes and assigned labels are illustrated in Figures 5, 6, and 7 below.

[12] Ibid.
[13] Ibid.

Figure 5: The Preparation Stroke[14]

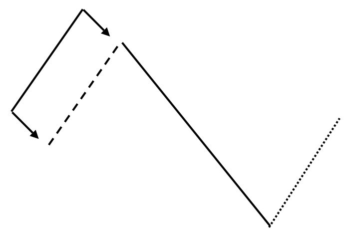


Figure 6: The Resurrection Stroke[15]

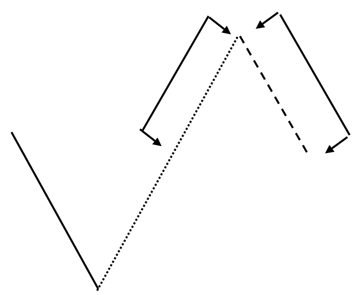
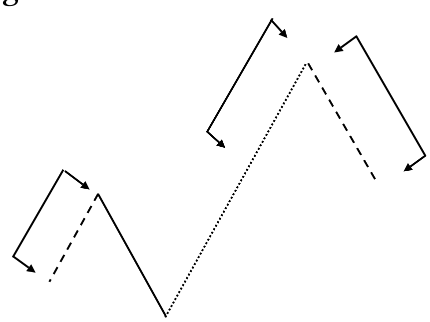


Figure 7: The Academic Stroke[16]



[14] Ibid.

[15] Ibid.

[16] Ibid.

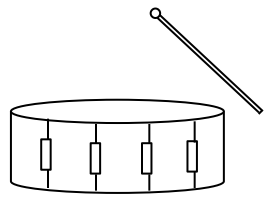
All of these stroke variations are important for the reader to understand since they occur frequently in percussion performance. Frequent use of these variations cause problems with pitch accuracy, unwanted timbre change, unwanted variation in volume, or an ensemble rhythmic issue, for instance, multiple players using multiple stroke variations to play one note at the same time.

While several variations of stroke motion exist, an important constant in percussion performance is volume. Obtaining the appropriate dynamic level on percussion instruments is directly related to correct striking motion.[17] The terms volume and dynamic level work interchangeably in music and within this study. McClaren suggests that dynamics can be achieved through stick height alone. If a loud dynamic is desired, a high stick height should be used. If a softer dynamic is desired, a low stick height should be used. Figure 8 below illustrates the use of stick height to achieve dynamics.

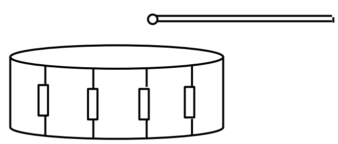
[17] McClaren, 7.

Figure 8: Formula for Volume[18]

Loud Volume = High Stick Height



Soft Volume = Low Stick Height

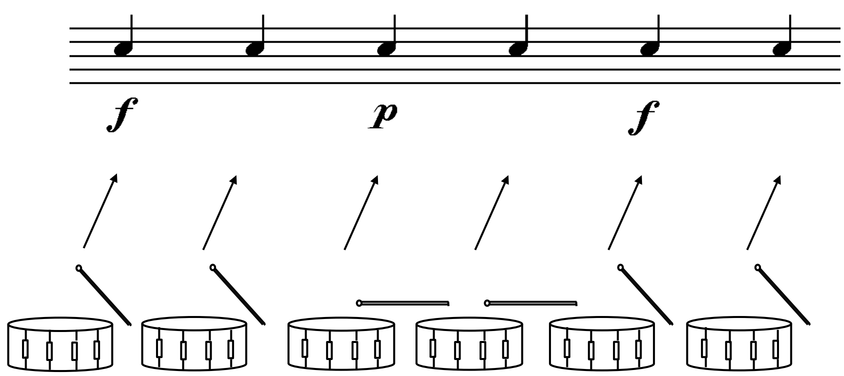


Advance preparation is the careful manipulation of stick or mallet height before a stroke motion occurs. The ending position for one motion will be the starting position for the next motion. Proper preparation in advance of a stroke will result in the ability to play with low stick velocity. Throughout the remainder of this document the speed at which the stick travels downward is labelled stick velocity or stroke velocity. These terms are interchangeable. Advance preparation eliminates wasteful motion, and when executed efficiently, the performer will visually demonstrate the appropriate stick height

[18] Ibid.

of a dynamic level before the dynamic level is actually performed. Figure 9 below illustrates a series of quarter notes performed at varying dynamics and the appropriate beginning stick height for each stroke motion. Note that the stick height illustrated represents the advance preparation of stick height before the dynamic level is performed.

Figure 9: Illustration of Advance Preparation



The utilization of the idea of advance preparation in percussion performance aims to minimize movement and use of energy, thus eliminating wasted motion that may result in an unnecessary variation of the piston stroke. A variation of the piston stroke, because of the inherent inclusion of wasteful motion, requires the performer to move the stick with a quicker motion than if a piston stroke without wasteful motion were used. A large amount of stroke velocity tends to produce a brittle, pinched sound, and a low amount of stroke velocity tends to produce a resonant, smooth sound. This is a result of the physical reaction of the object being struck and the amount of stroke velocity used. Wasted motion present in a stroke correlates in relative fashion to the amount of velocity present, ultimately affecting the quality of sound produced.

The first portion of data collection in this study strictly focused on the difference in stroke velocity found in the stroke variations discussed by Stevens. Although sound quality may be affected by stroke velocity, and the apparent relationship between stroke velocity and sound quality was one of the catalysts in the design of this research, the primary focus of this study was to determine whether stroke velocity could be quantified using the methods outlined in Chapter 3. When determined possible or impossible using these methods, the relationship of stroke velocity and sound quality could be further explored in another study.

The second portion of data collection in this study constituted measuring stroke velocity of two-mallet marimba excerpts, adhering to the methods outlined in Chapter 3. As stated above, although sound quality is an issue that all percussionists manipulate in a performance setting, the focus of this study was to determine whether the outlined methods for data collection are accurate and efficient in measuring stroke velocity. It was the author's intent to discover whether the relationship of stroke velocity and sound quality might be explored in future research. Additional possible relationships between varying performance issues and stroke velocity will also be discussed in Chapter 6.

CHAPTER II

REVIEW OF PREVIOUS RESEARCH

A minimal amount of research in the area of stick motion in percussion performance exists. Even less research is available in the area of stroke velocity in marimba performance. Through a review of previous research performed in this area of study, Sofia Dahl is a researcher and drummer whose name appears most frequent. Her study, *The Playing of An Accent: Preliminary Observations from Temporal and Kinematic Analysis of Percussionists*, illustrates the movements and timing of a percussionist's stick when playing an interleaved accent by studying three professionals and one amateur.[19] Dahl explains that a common way to denote the character of a stroke preceding a sudden change in dynamic level is to use the terms *upstroke* and *downstroke*.[20] The use of the terms upstrokes and downstrokes is synonymous with the term striking motion used in Chapter 1 of this study. These terms, upstroke and down stroke, describe the desired final position of the stick in preparation for the next stroke, also termed stick height and advance preparation in chapter 1 of this study. Finally, Dahl explains that the upstroke and the down stroke, along with a soft stroke called a *tap*, are commonly

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[19] Dahl, Sofia (2000). The Playing of An Accent: Preliminary Observations from Temporal and Kinematic Analysis of Percussionists. *Journal of New Music Research*, 29, 225.

[20] Ibid., 226.

executed by percussionists to help plan and carry out the correct movements for a successful performance. This is described as advanced preparation in Chapter 1.

Dahl's inclusion of these stroke motions, although slightly different in terminology as compared to those discussed in Chapter 1, intend to highlight the importance of striking motion, stick height, and advanced preparation in percussion performance. In her study, Dahl used time lapse photography to track the path of a drumstick set in motion by a percussionist playing sequential hits on a drum, with an accent on every fourth hit. Dahl's study and discussion of stroke motion, in addition to the lack of information found on stroke velocity in a review of previous research, directly influenced the development and methodology of this project.

A second study that influenced the design of this project was Diana Young's and Ichiro Fujinaga's research titled, *AoBachi: A New Interface for Japanese Drumming.*[21] Young and Fujinaga embedded electronics in traditional Japanese drumsticks called AoBachi. The electronically embedded AoBachi measured path of travel in the air, called gesture-tracking, and also stick motion and speed. This data was wirelessly captured using Bluetooth technology similar to that of a mobile phone or laptop device.[22]

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[21] Young, D., Fujinaga, I. AoBachi: A New Interface for Japanese Drumming. *Proceedings of the 2004 Conference on New Interfaces for Musical Expression (NIME04)*, 2.

[22] Ibid.

Young and Fujinaga designed the AoBachi interface to preserve natural feel and weight. The AoBachi, measuring approximately 20 inches long and 1.5 inches in diameter, were hollowed at one end in order to create an enclosure for the necessary electronics.[23] To encourage the traditional techniques of Japanese drumming, the AoBachi were designed to be lightweight, small, and wireless. Due to the size of these sticks, the gesture sensing system had to also be minimal in size. Young and Fujinaga equipped the AoBachi with technology that could measure 2 axes of angular velocity and acceleration, but did not measure the twisting motion of the stick about its own axis since such a motion is less important to taiko technique..[24] Throughout the study two players used two sticks each, totaling four sticks measured to capture data.[25]

The prototypes in the Young and Fujinaga study included 4 sensors per stick that measured five independent degrees of freedom, 2 two-axis accelerometers capable of measuring a full-scale range with a variation of +/– 2G, and two single-axis Murata Gyrostar gyroscopes to reflect the angular velocity of the sticks.[26]

Young and Fujinaga's study was a pilot experiment to measure the success of the AoBachi prototype, and lacked prescribed research design methods. Their study influenced the design of the current project in exploring the possibility of measuring

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[23] Ibid.
[24] Ibid.
[25] Ibid.
[26] Ibid.

stroke velocity for performance on the marimba. Young and Fujinaga's treatment of data and collection methods were helpful and additionally influenced the current study.

Finally, a study in the area of sports medicine titled *Kinematic Quantitation of the Patellar Tendon Reflex using a Tri-axial Accelerometer* influenced the design of the current study.[27] In this research project, the angular speed of the knee joint is calculated from the acceleration data generated in response to the tapping force applied to the patellar tendon, or knee cap, with a customized tendon hammer, and was measured using a tri-axial accelerometer placed at the ankle joint.[28] The data was collected using a signal analyzer and a personal computer.

In the Mamizuka, et al. study, each participant sat upright in a customized seat, and the right ankle joint was fitted with a short leg brace. The motions of the trunk and extremities were not restrained so that the participant's motion could be naturally elicited by muscle contraction. A tri-axial accelerometer was fixed to the brace, and the patellar tendon was manually tapped with a hammer fitted with a force sensor to measure the force impact on the kneecap. Data was then collected from both the accelerometer and the hammer.[29]

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[27] Mamizuka, N., Sakane, M., Kaneoka, K., Hori, N., & Ochiai, N. (2007) Kinematic Quantitation of the Patellar Tendon Reflex Using a Tri-axial Accelerometer. *Journal of Biomechanics*, 40, Issue 9, 2107.

[28] Ibid.

[29] Ibid., 2108.

Participants remained fully relaxed during the procedures. During one procedure, the tendon was tapped a total of 25 times with random forces ranging from 10N (Neutons) to 80N. The reflex response, which lasted for a maximum of 5 seconds, was not inhibited and was allowed to stop naturally.[30]

The research design of Mamizuka, et al. influenced the current research project. The seated position of the participant correlates with the comfortable, natural standing position of the marimbist in this study. The use and placement of an accelerometer in the patellar tendon reflex study is similar to the current study, except that the accelerometer was placed on the top of the hand rather than the ankle. In addition, acceleration data is displayed along three axes of movement and then combined into one composite measurement of stroke velocity.

[30] Ibid.

CHAPTER III

OUTLINE OF PROCEDURES

The purpose of this study was to determine if stroke velocity used in two-mallet marimba performance can be quantified. Although a correlation between the piston stroke, a variation of the piston stroke, and the resulting stroke velocity has been discussed, no attempt was made to determine the exact relationship between stroke velocity and sound quality. The purpose of this study was to determine whether stroke velocity can be measured using the research design discussed in this chapter.

Equipment

The equipment used to measure stroke velocity is included in List 1 below.

List 1: Equipment and Materials Used in Study

1. 5-octave Yamaha marimba (YM-5100A)
2. 1 pair of *Marimba One* brand *Katarzyna Mycka* model (KMB2) marimba mallets
3. 1 copy of *The Book of Percussion Audition Music for the 21st Century* written by Dr. Cort McClaren and Dr. Nathan Daughtrey[31]

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[31] Cort McClaren and Nathan Daughtrey, *The Book of Percussion Audition Music for the 21st Century* (North Carolina: C. Alan Publications, 2006)

4. 1 copy of *Concerto No.1 for Marimba: Gate to Heaven* by David R. Gillingham[32]
5. 1 tri-axial accelerometer module
6. 1 *MacBook* laptop equipped with *iMovie* software
7. 1 personal computer equipped with *LabView 5.1* software
8. 1 roll of adhesive medical gauze/tape

Set-up of Equipment

Once the marimba placement was determined, the personal computer and subsequent accelerometer interface equipment was placed approximately ten feet behind the performer. The MacBook laptop was placed at the front of the marimba to digitally video record the data collection process.

The tri-axial accelerometer was first attached to the top of the performer's right hand using adhesive medical gauze and tape in a manner to avoid constricting the performer's ability to execute proper striking motion. Location of the accelerometer on top of the performer's hand and the distance from the accelerometer to the head of the mallet was measured to ensure accuracy of data collection from excerpt to excerpt. Equipment was removed and repositioned for performance of multiple excerpts. Cables connecting the accelerometer to the personal computer were run along the side of the performer's forearm and secured using medical gauze and tape. Once the equipment

[32] Gillingham, David R., Concerto No.1 for Marimba: *Gate to Heaven* (North Carolina: C. Alan Publications, 1998)

was properly secured, the performer's fulcrum, point of hand contact on the marimba mallet, was marked on the mallet shaft to ensure data accuracy throughout the data collection.

Figure 10: Performer's Hand and Placement of Accelerometer

Data Collection

First, a low velocity piston stroke executed with the performer's right hand was measured. Second, a high velocity piston stroke was measured using the same method.

Third, the three variations of a piston stroke, outlined in Chapter 1, were measured; the preparation stroke, the resurrection stroke, and the academic stroke respectively. All three of these strokes were measured only with the right hand, and every attempt to accurately demonstrate these stroke variations was made.

Fourth, data was collected for the right hand and the left respectively for the last eight measures from the *Keyboard Audition Etude #2* from the publication, *The Book of Percussion Audition Music for the 21st Century* of McClaren and Daughtrey. Figure 11 outlines the *Keyboard Audition Etude #2* excerpt.

Figure 11: *Keyboard Audition Etude #2, meas. 21 – 29* [33]

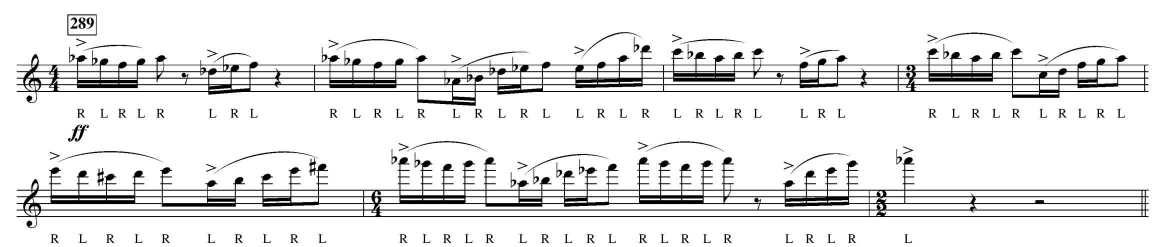
Small variation in dynamics, lack of tempo fluctuation, and minimal range of pitch involved made the eight measures of this etude ideal for measurement. In addition, a limit of eight measures were chosen because the data collection frequency of the accelerometer was set to collect data every one-thousandth of a second, resulting in

[33] McClaren and Daughtrey. Used with permission.

a very large accumulation of numerical values. The *LabView 5.1* software is capable of handling a limited amount of accumulated numerical data. Data was collected in the same fashion used when measuring variations of the piston stroke.

The *Concerto No.1 for Marimba: Gate to Heaven* excerpt was chosen because it is an excellent example of a two-mallet passage found in a contemporary marimba concerto, and has practical application to modern day marimba performance. Data was collected for measures 289 to 295. Figure 12 below notates the *Gate to Heaven* excerpt.

Figure 12: *Concerto No.1 for Marimba: Gate to Heaven*, meas. 289 – 295 [34]



[34] Gillingham. Used with permission.

CHAPTER IV

TREATMENT AND REPORT OF COLLECTED DATA

The purpose of this study was to determine if stroke velocity used in two-mallet marimba performance can be quantified. A correlation between stroke velocity and sound quality was not attempted. This study was designed to determine whether stroke velocity can be measured using the research design discussed in this chapter.

Chapter 4 includes a report of data collected using the research design outlined in Chapter 3. Using *LabView 5.1* data collection software, raw acceleration values were collected Raw values were collected in three separate axes of orientation. The x-axis values indicate a change in acceleration along the horizontal axis, y-axis values indicate a change in acceleration along the vertical axis, and z-axis values indicates a change in acceleration along the axis running perpendicular to both the x and y axes respectively, resulting in data collection within a three dimensional space. Yielding three data values for every one thousandth of one second, data values were collected at a rate of one data point every one thousandth (1/1000) of a second for all three axes, and were measured in volts.

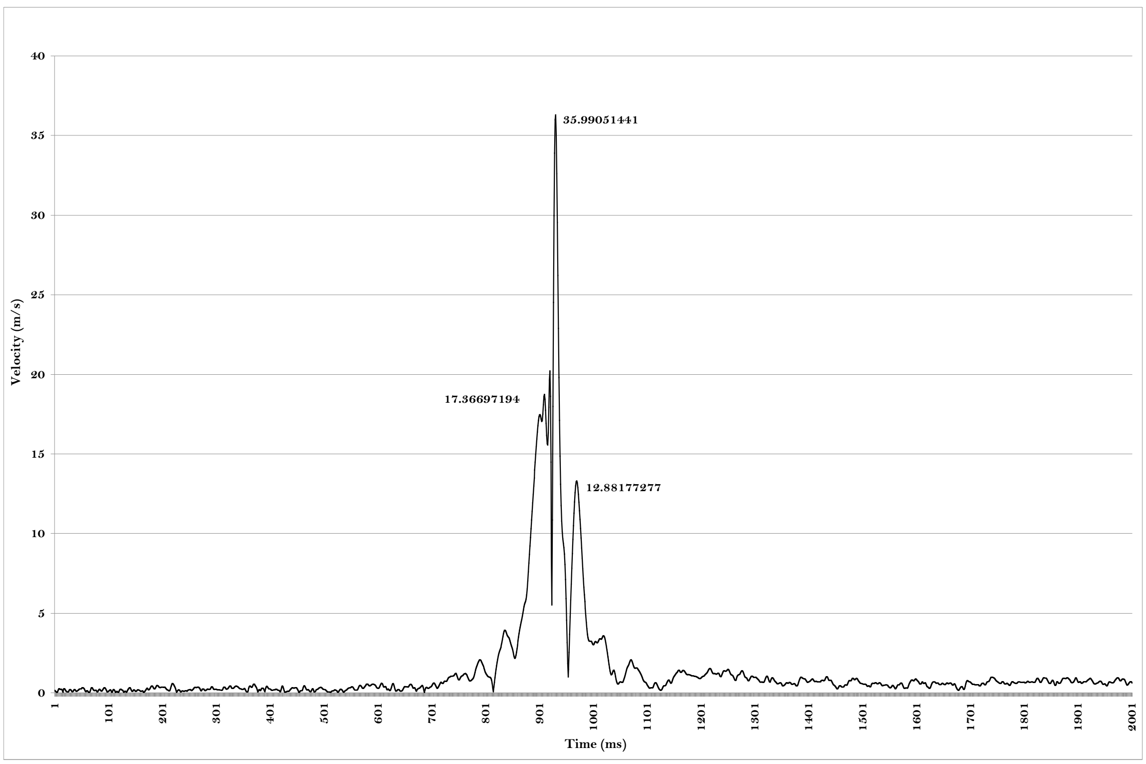
Once raw data values were collected, the first one hundred data values for all three axes determined an average difference from the value of 2.5 volts, which is what the accelerometer measures at rest. The average of the first one hundred data values was then subtracted from all remaining data values in order to establish a zero baseline for raw acceleration values. A subtraction of this average from all data values produces an accurate measurement of variation in stroke acceleration from a resting position of approximately 0 volts.

Establishing a zero baseline, a fourth order low-pass Butterworth filter was applied to all data. The low-pass Butterworth filter provides a smoother form of data signal and removes any short-term noise present, leaving only a long-term trend of accurate data. The low-pass filter eliminates random errors involved in data collected involving extreme high and low frequencies. Once application of the low-pass filter takes place, an integral of acceleration is calculated for the first x, y, and z axes and converted to a velocity magnitude value. This integral is applied to the remaining data values found in each stroke and excerpt.

Data will be presented in the same order that it was collected as outlined in Chapter 3: first, data for a low velocity piston stroke and a high velocity piston stroke; second, data for the preparation stroke, the resurrection stroke, and the academic stroke. Finally, line graphs illustrate data for two marimba excerpts, the McClaren/Daughtrey excerpt and the Gillingham excerpt respectively.

Figure 13 below displays velocity magnitude values found in a low velocity piston stroke. A low velocity piston stroke is a stroke that starts at a pre-determined height, moves down towards the marimba bar, and returns to the original mallet height with a low amount of velocity present in both the stroke and the recovery.

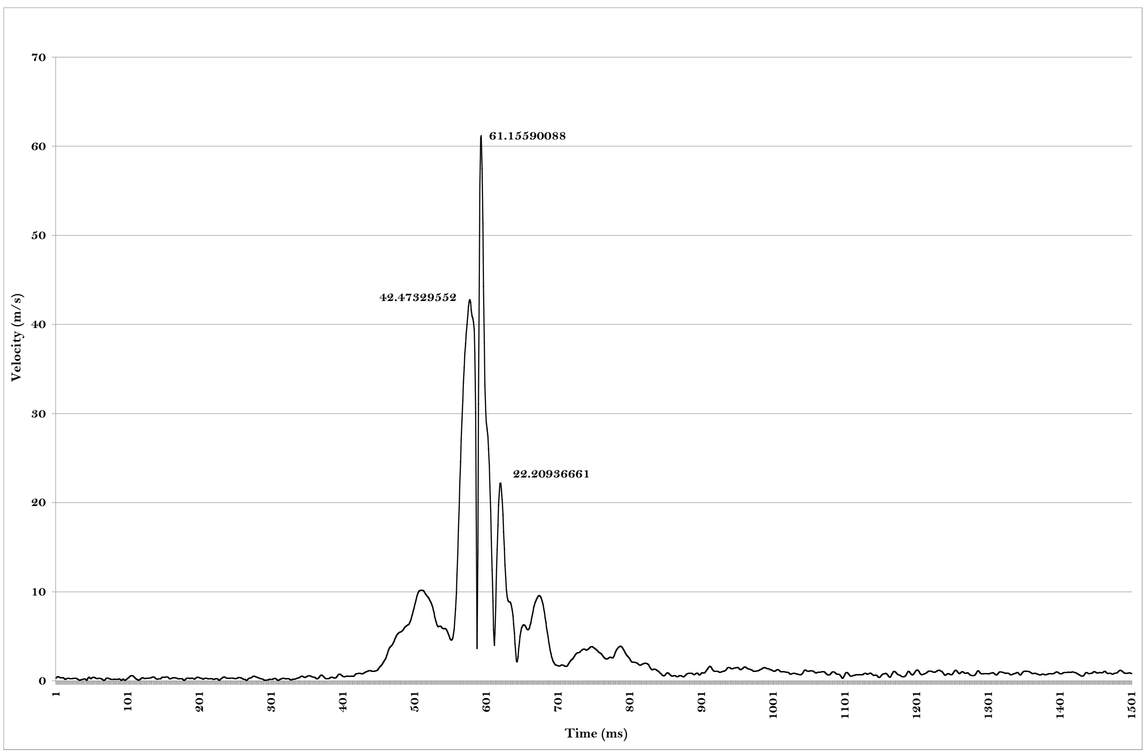
Figure 13: Velocity Magnitude Values of a Low Velocity Piston Stroke



A velocity magnitude, measured in meters per second, of 35.99051441 m/s was reported as the largest velocity magnitude found in this stroke. A display of two additional velocity magnitude values appear in numerical form on the graph because of the disruption of a smooth increase or decrease in velocity magnitude, and to aid in the reader's interpretation of the provided data.

Below, Figure 14 illustrates the velocity magnitude values found in a high velocity piston stroke. Including a deliberate increase in stroke velocity, a high velocity piston stroke was performed with the same stick height as the previous stroke

Figure 14: Velocity Magnitude Values of a High Velocity Piston Stroke



A velocity magnitude of 61.15590088 m/s was the highest velocity magnitude measured during the high velocity piston stroke. Two other velocity magnitude values are displayed in this figure to aid in the reader's interpretation of the data. These data values represent peak velocity magnitude values found at a disruption in the fluidity of a smooth increase and decrease in velocity magnitude.

Figure 15 below displays velocity magnitude values found in a piston stroke that begins with a preparation upward before the stroke moves downwards toward the marimba bar. This is named a preparation stroke, and is discussed in Chapter IX of Part 1 of *Method of Movement for Marimba* by Leigh Howard Stevens.[35] A preparation stroke includes an initial movement upward from the pre-determined stick height set by the performer. A preparation stroke differs from a correctly executed piston stroke because it includes a preparation upward, instead of the beginning motion of the stroke moving down towards the marimba bar before returning to the initial stick height. Refer to Figure 5 in Chapter 1 for an illustration of a preparation stroke.

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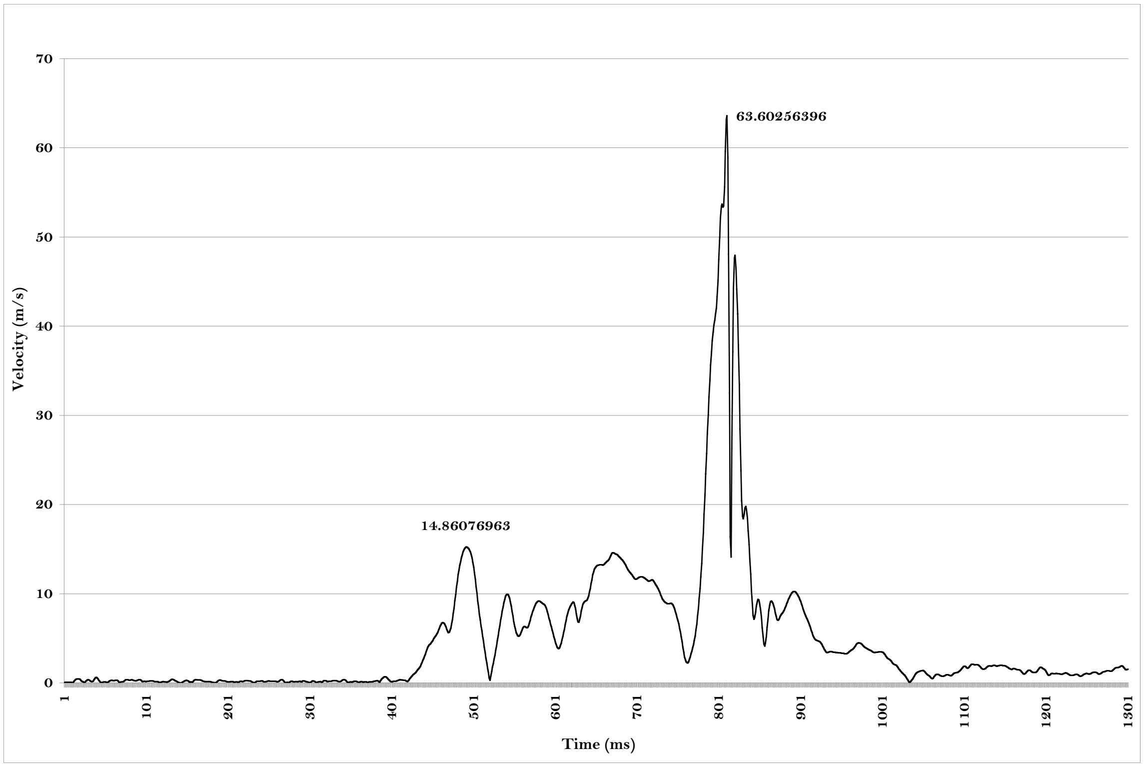
[35] Leigh Howard Stevens, *Method of Movement for Marimba*, 4th ed. (Leigh Howard Stevens, 1997), 16.

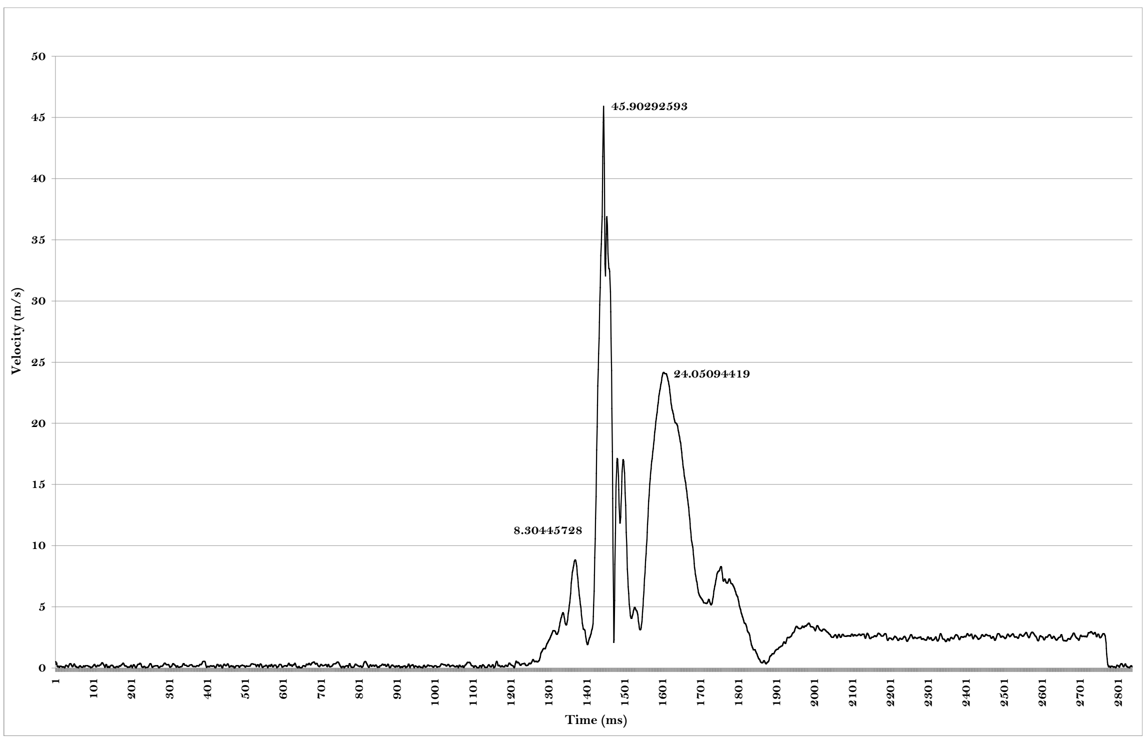
Figure 15: Velocity Magnitude Values of a Preparation Stroke



The highest velocity magnitude present in the preparation stroke measured 63.60256396 m/s. In addition to the measured velocity value, an initial spike in velocity magnitude measured 14.86076963 m/s. Note the difference in initial interruption in velocity magnitude of the preparation stroke in comparison to both the low velocity and high velocity piston strokes.

Figure 16 below illustrates velocity magnitude values found during the execution of a resurrection stroke. Initiated in the same fashion as a correctly executed piston stroke, the resurrection stroke beginnings with motion moving toward the marimba bar. Once the stroke recovers to the pre-determined stick height, it passes this pre-determined height and prepares for the next stroke to occur. Refer to Figure 6 in Chapter 1 for the stroke motion path of travel present in a resurrection stroke.

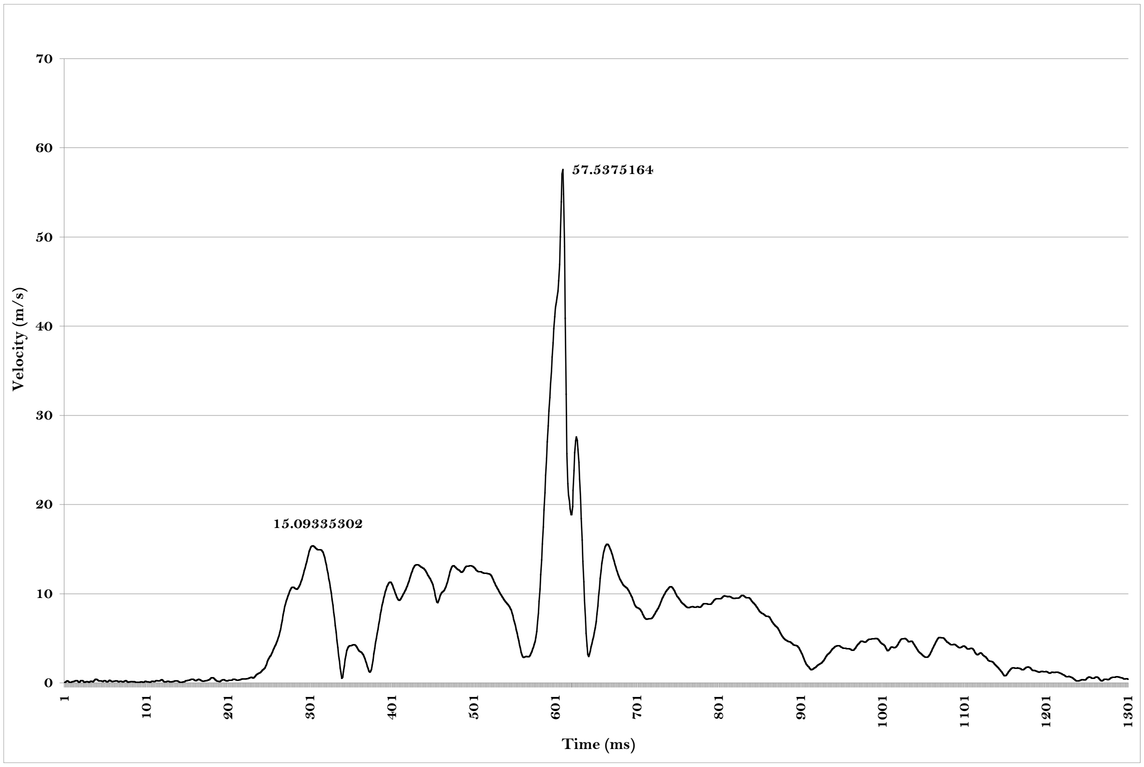
Figure 16: Velocity Magnitude Values of a Resurrection Stroke



The highest velocity magnitude value found in the resurrection stroke was 45.90292593 m/s. Two additional velocity values appear within Figure 16 to aid in the reader's interpretation of the velocity magnitude values. The resurrection stroke contained a significantly different path of travel in comparison to the low velocity piston stroke, the high velocity piston stroke, and the preparation stroke respectively. The second velocity magnitude value of 24.05094419 m/s is most likely a result of the preparation that occurred after the recovery of the resurrection stroke.

Figure 17, below, displays velocity magnitude values of an academic stroke. The academic stroke includes both a preparation upward, an increased stick height during the recovery, and another preparation at the end of the academic stroke. The academic stroke includes a stroke with both preparation and lift, and is a combination of the preparation stroke and the resurrection stroke.

Figure 17: Velocity Magnitude Values of an Academic Stroke



The academic stroke yielded a high velocity magnitude value of 57.5375164 m/s. A much larger duration of low level velocity values were found during the academic stroke, and the peak of a fluctuation within a smooth increase and decrease in velocity magnitude values is numerically labeled for more accurate interpretation. Note the difference in shape of the academic stroke in comparison to the low and high velocity piston strokes, the preparation stroke, and the resurrection stroke.

Chapter 5 outlines a detailed interpretation of collected data. Preservation of a similar pre-determined stick height was kept during the execution of the low and high velocity piston strokes, the preparation stroke, the resurrection stroke, and the academic stroke, The piston stroke, whether containing a low or high amount of stroke velocity, and the variations of the piston stroke can occur at any stick height.

Figure 18 below illustrates velocity magnitude values measured for the right hand during the performance of *Keyboard Audition Etude #2*, and Figure 19 illustrates velocity magnitude values measured for the left hand. Velocity values were rounded to the one hundredth place value for an uncluttered display. Refer to Figure 11 in Chapter 3 for the musical notation of the *Keyboard Audition Etude #2* excerpt.

Figure 18: Right Hand Velocity Magnitude Values of ***Keyboard Audition Etude #2*** **Excerpt**

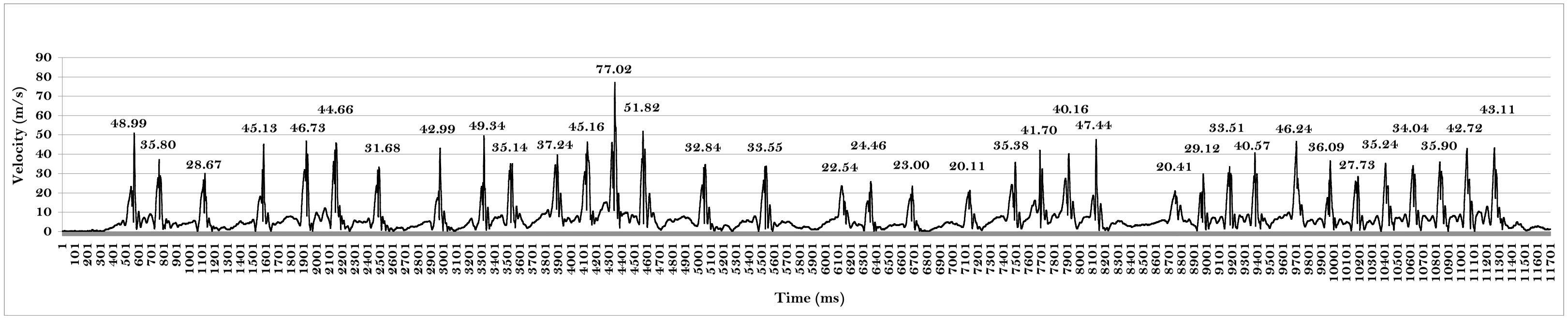
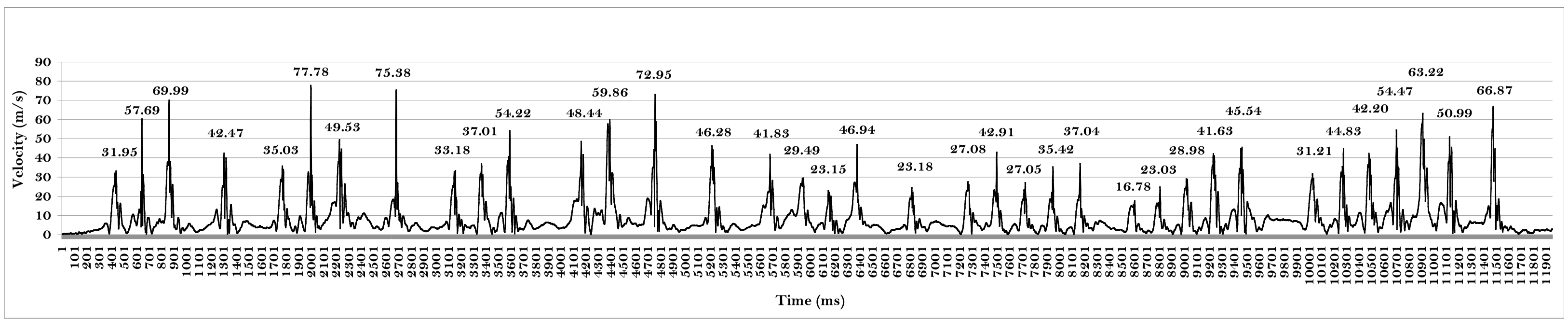


Figure 19: Left Hand Velocity Magnitude Values of ***Keyboard Audition Etude #2*** **Excerpt**



Each instance of a spike in velocity magnitude displayed within Figure 18 through 21 indicates the largest amount of velocity present within an individual stroke performed. The numerical value of stroke velocity magnitude is provided directly above the line display. Thirty-six strokes were executed during the *Keyboard Audition Etude #2* excerpt with the right hand, and thirty-seven strokes with the left hand. A maximum right hand velocity magnitude value measured 77.02 m/s. A minimum velocity magnitude value measured 20.41 m/s. The maximum and minimum right hand velocity magnitude values are located within Figure 18. A maximum left hand velocity magnitude value for the *Keyboard Audition Etude #2* excerpt measured 77.78 m/s. A minimum velocity magnitude value measured 16.78 m/s. Maximum and minimum left hand velocity magnitude values are located in Figure 19.

Figures 18 through 21 serve as a report of measured stroke velocity. Chapter 5 constitutes a more detailed interpretation of the collected data, and contains a display of both the musical notation of the marimba excerpts and velocity magnitude values to aid in a more clear interpretation of data.

Figure 20 below contains right hand velocity magnitude values for the Concerto No.1 for Marimba: *Gate to Heaven* excerpt. Figure 21 contains values for the left hand. A large increase in velocity magnitude indicates a single executed stroke. Numerical data values displayed above the increases in velocity reports the highest velocity magnitude value measured. Velocity magnitude values were rounded to the one hundredth place value. Refer to Figure 12 in Chapter 3 for the musical notation of the *Gate to Heaven* excerpt.

Figure 20: Right Hand Velocity Magnitude Values of *Concerto No.1 for Marimba: Gate to Heaven* **Excerpt**

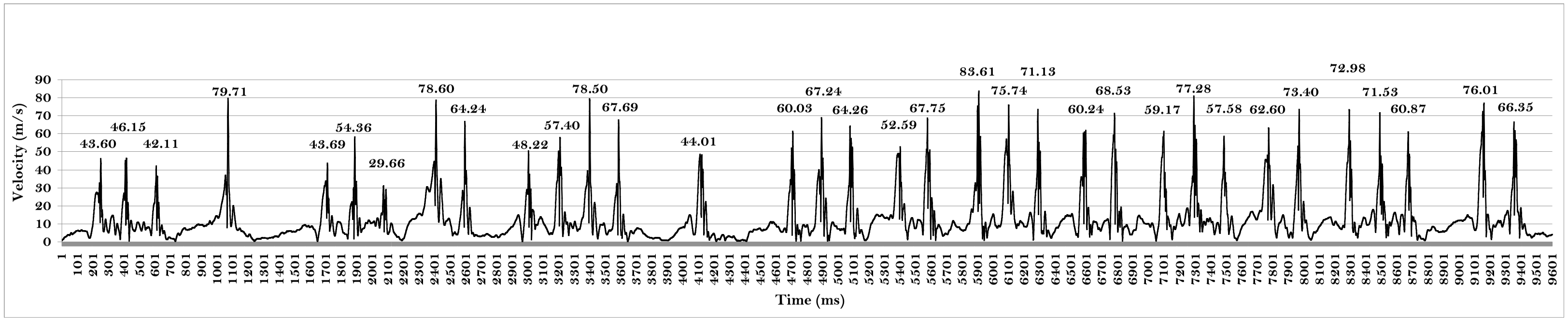
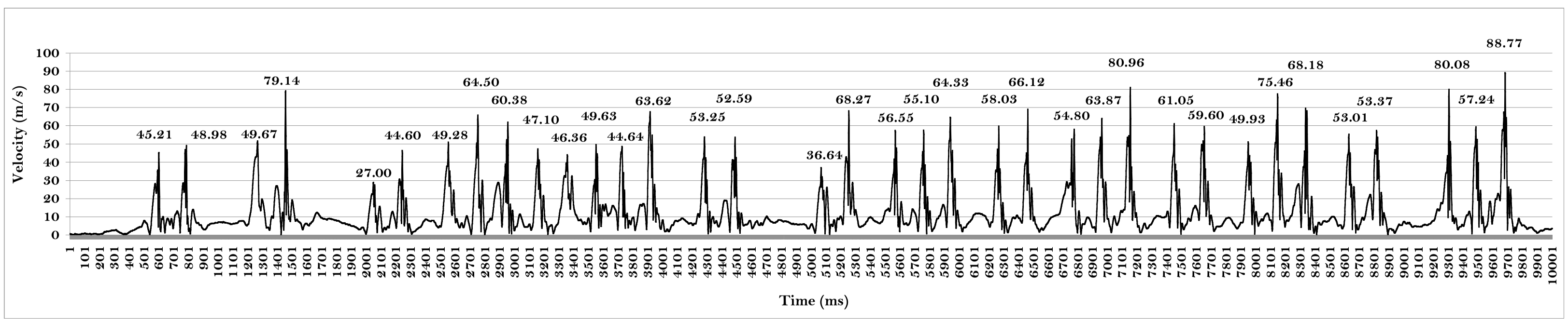


Figure 21: Left Hand Velocity Magnitude Values of *Concerto No.1 for Marimba: Gate to Heaven* **Excerpt**



During the performance of the *Gate to Heaven* excerpt, thirty-four strokes were executed with the right hand, and thirty-six strokes were executed in the left hand. A maximum right hand velocity magnitude value measured 83.61 m/s. A minimum velocity magnitude value measured 29.66 m/s. These values are located in Figure 20. A maximum left hand velocity magnitude value measured 88.77 m/s, and a minimum velocity magnitude value measured 27.00 m/s. These velocity magnitude values are both located in Figure 21 above. A detailed interpretation and display of both the musical notation and the velocity magnitude values of the *Gate to Heaven* excerpt appear in Chapter 5.

CHAPTER V

INTERPRETATION OF COLLECTED DATA

The purpose of this study was to determine if stroke velocity used in two-mallet marimba performance could be quantified. Although a correlation between the piston stroke, variations of the piston stroke, and the resulting stroke velocity has been discussed, no attempt in this study was made to determine the exact relationship between stroke velocity and sound quality. The design of this study was intended to determine whether stroke velocity could be measured using the procedures discussed in Chapter 3.

In this chapter, data interpretation occurs in the same order that it was collected. Relationships between the low velocity and high velocity piston stroke, the preparation stroke, the resurrection stroke, and the academic stroke appear. Second, relationships between stroke path of travel, and the concept of conservation of energy and advance preparation are made. Third, an evaluation and interpretation of the data collected during the performance of two marimba excerpts appear. A discussion about selected musical gestures and figures found within these excerpts, and a correlation between these figures and the velocity magnitude values present appear in this chapter. An attempt to correlate the ideal of sound quality and stroke velocity is not made.

To aid in the interpretation of the collected data values, Table 1 below provides velocity magnitude values beginning at 0 m/s and ending at 100 m/s, increasing at increments of 5 m/s in column 1, and the corresponding value converted from meters per second to miles per hour in column 2. This conversion was done using the formula *velocity* * 2.24 = *speed.* (meters per second * 2.24 = miles per hour) This conversion is supplied to aid in the reader's understanding of velocity as a unit of measurement, as it is not commonly used in a field of study other than physics. The use of a unit of measurement such as miles per hour is used quite often, and may aid the reader in understanding the collected data. The application of a unit of measurement such as miles per hour is intended to aid in the reader's interpretation of data, and is not used for any other purpose. Data values converted to miles per hour are found in parenthesis directly after the corresponding velocity magnitude value originally displayed in a unit of measurement of meters per second.

Table 1: Conversion of Velocity Values (m/s) to Speed (mph)

0 m/s	0 mph
5 m/s	11.2 mph
10 m/s	22.4 mph
15 m/s	33.6 mph
20 m/s	44.8 mph
25 m/s	56 mph
30 m/s	67.2 mph
35 m/s	78.4 mph
40 m/s	89.6 mph
45 m/s	100.8 mph
50 m/s	112 mph
55 m/s	123.2 mph
60 m/s	134.4 mph
65 m/s	145.6 mph
70 m/s	156.8 mph
75 m/s	168 mph
80 m/s	179.2 mph
85 m/s	190.4 mph
90 m/s	201.6 mph
95 m/s	212.8 mph
100 m/s	224 mph

The Low Velocity Piston Stroke

The low velocity piston stroke, figure 13 found in chapter 4, contained a maximum velocity magnitude value of 35.99 m/s (80.42 mph). All subsequent data values were rounded to the one hundredth place value. The low velocity piston stroke was performed at an approximate stick height of twelve inches above the marimba bar.

Stroke motion was executed in a relaxed manner and contained only a minimal amount of stroke velocity. The low velocity piston stroke took approximately three thousandth of one second to execute, and measured along the x-axis from approximately 800 ms (milliseconds) to 1100 ms. Low lying data values occurring between x-value 1 ms to 799 ms, and 1101 ms to 2001 ms are a result of unintentional minute movement of the mallet before and after the stroke, and a low level occurrence of frequency fluctuation common with the type of equipment used in this study. To enable a centered illustration of the low velocity piston stroke within Figure 13, these data values are displayed.

The numerically displayed data value present in Figure 13 of 17.37 m/s (38.91 mph) measured during the downward portion of the low velocity piston stroke, and 12.88 m/s (28.67 mph) during the recovery of the low velocity piston stroke, is likely a result of a small fluctuation within the fluid movement of the respective parts of the low velocity piston stroke, and was not an intentional variation within the stroke motion. In addition, the small and sudden change in velocity magnitude present during the recovery may be a result of a slight flex in the mallet shaft and within the performer's hand as the recovery of the mallet stopped and returned to the original stick height found at the beginning of the low velocity piston stroke.

The High Velocity Piston Stroke

Within Figure 14 found in Chapter 4, data measured during the execution of a high velocity piston stroke is located. A maximum velocity magnitude value of 61.16 m/s (137.00 mph) was measured. The high velocity piston stroke contained a 25.17 m/s (56.38 mph) increase in maximum stroke velocity compared to the low velocity piston stroke. The high velocity piston stroke occurred between approximately 450 ms and 825 ms, almost identical to the duration of time the low velocity piston stroke was executed. Low lying data values before and after the stroke were most likely a result of minute and unintentional movement occurring before and after the stroke, and are also present in Figure 14 for the display of the stroke within the figure.

The numerically displayed values found before and after the maximum velocity value is likely a result of a slight and unintentional variation within the smooth path of travel towards the marimba bar and back to the original stick height. The stick height used for the execution of the high velocity piston stroke was approximately twelve inches. The slight fluctuations noted are significantly increased in comparison to the low velocity piston stroke, and are likely a result of the release of a greater amount of potential energy initial present before execution of the stroke.

The Preparation Stroke

The preparation stroke, Figure 15 found in Chapter 4, displays a different path of travel as compared to the low velocity piston stroke and the high velocity piston stroke. The preparation stroke contained an initial velocity magnitude value of 14.86 m/s (33.29 mph), and was most likely the preparation segment of this particular piston stroke variation. A similar velocity magnitude occurs a second time before the stroke itself, possibly constituting the variance of velocity during the change in direction of the stroke from a resting position upwards, and then back down towards the beginning stick height established before motion occurred.

During the preparation stroke, a maximum velocity magnitude value measured 63.60 m/s (142.46 mph). Although a high measurement of velocity in comparison to the low velocity piston stroke, this value does not necessarily represent the inability for this stroke to contain low velocity, as the execution of a single stroke can theoretically contain a large variance in velocity magnitude. Of importance is the path of travel of the preparation stroke, and the significant affect this path of travel made during the attempted steady increase and decrease of velocity magnitude during the stroke and recovery portions respectively. In addition, while a relatively moderate amount of velocity is present, the length of time for the preparation stroke to occur was longer than both the low velocity piston stroke and the high velocity piston stroke. The preparation stroke occurred between the x-axis values of approximately 410 ms and 1025 ms. Approximate elapsed time of the preparation stroke was 615 ms, or .615 seconds. The elapsed time of the preparation stroke was .240 seconds longer than the high velocity piston stroke, and .315 seconds longer than the low velocity piston stroke. This may indicate that variations of the piston stroke, when velocity is relatively equal during successive strokes, result in an elongated elapsed time of execution, and may result in inconsistent timing when used in an ensemble setting.

<u>The Resurrection Stroke</u>

The resurrection stroke, Figure 16 of Chapter 4, contains a maximum velocity magnitude value of 45.90 m/s (102.82 mph). In comparison to the low velocity piston stroke, the high velocity piston stroke, and the preparation stroke, this may be of minimal significance. A mature percussionist can vary stroke velocity with relative ease when one stroke is isolated. Of greater importance in Figure 16 is the presence of an elevated velocity magnitude during the recovery and subsequent preparation occurring after the stroke. During a large spike in velocity magnitude occurring after the stroke at an x-value of approximately 1601 ms, a velocity magnitude value of 24.05 m/s

(53.87 mph) occurred. This is likely a result of the increase in distance of stroke recovery compared to the stick height of the down stroke, and the resulting preparation for another stroke afterwards, inherent of this stroke variation.

The resurrection stroke occurred between x-axis values of approximately 1250 ms and 1875 ms, constituting an elapsed time duration of .625 seconds, and is approximately the same duration as the preparation stroke. Empirical data suggests that the preparation stroke and the resurrection stroke, when velocity magnitude values are similar, yield the same approximate duration of time to execute.

<u>The Academic Stroke</u>

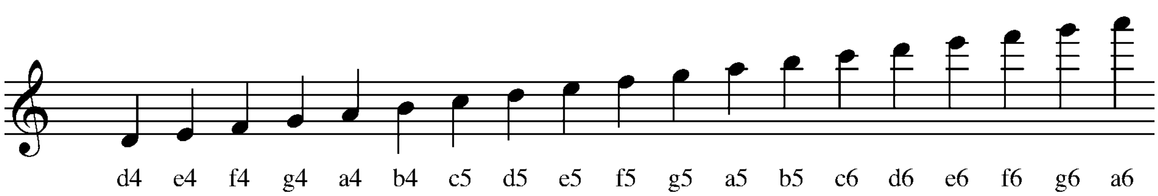
The academic stroke, Figure 17 in Chapter 4, contained a maximum velocity magnitude value of 57.54 m/s (138.10 mph). Like the resurrection stroke, this maximum velocity magnitude is not of significant importance in comparison to the low velocity piston stroke, the high velocity piston stroke, the preparation stroke, and the academic stroke. This is because the isolation of a single stroke and the ability to vary the stroke velocity during the execution of such a stroke. Of importance is the elongated duration of time that the academic stroke was executed. The academic stroke began at an x-axis value of approximately 225 ms, and ended at 1150 ms. Duration of time for the academic stroke to be executed was longer than the four strokes previously measured.

The academic stroke took approximately .925 seconds to execute, and included both a substantial velocity magnitude variation during the preparation and the recovery segment of the stroke. The fluctuation in velocity magnitude measured at approximately 15 m/s, and lasted approximately 350 ms during the preparation, and 325 ms during the recovery respectively. A notable amount of low velocity magnitude values found during the preparation and recovery of the academic stroke are present. Additional stroke motion may hinder the ability of a performer to achieve sound with little effort, and supports the notion that advance preparation, and the removal of wasted stroke motion, enables a percussionist to achieve sound with a stroke using one motion toward the instrument, and a recovery that returns to the original pre-determined stick height.

The velocity magnitude values collected during the execution of a low velocity piston stroke and a high velocity piston stroke, the preparation stroke, the resurrection stroke, and the academic stroke, although valuable, tend to be arbitrary because of the nature of the isolation of each stroke, and the absence of a terminal stroke velocity to play multiple strokes in succession. Data collected while performing these five strokes are of importance because the preparation stroke, the resurrection stroke, and the academic stroke show an obvious addition of wasted motion in comparison to a stroke motion that simply contains a stroke and a recovery. This is important to a percussionist when preparing in advance to play different dynamics, as the addition of wasteful motion leads to the unintentional execution of varied dynamics, and causes timing issues in ensemble playing. In addition, for instance, when moving horizontally from one drum to another during timpani performance, the addition of this wasteful motion tends to lead to incorrect playing areas or a change in timbre.

Figure 22 below includes pitch and respective octave identification to aid in interpreting collected data, and allows for a clearer discussion of data while referencing the appropriate musical notation. This octave identification system is used often in music theory research and is intended to aid in the reader's interpretation of specified data. Octave numbering begins on the pitch *C* of any given octave, and progresses in numeric order as pitch increases. Accidental markings, ♭ or ♯ signs do not affect octave identification.

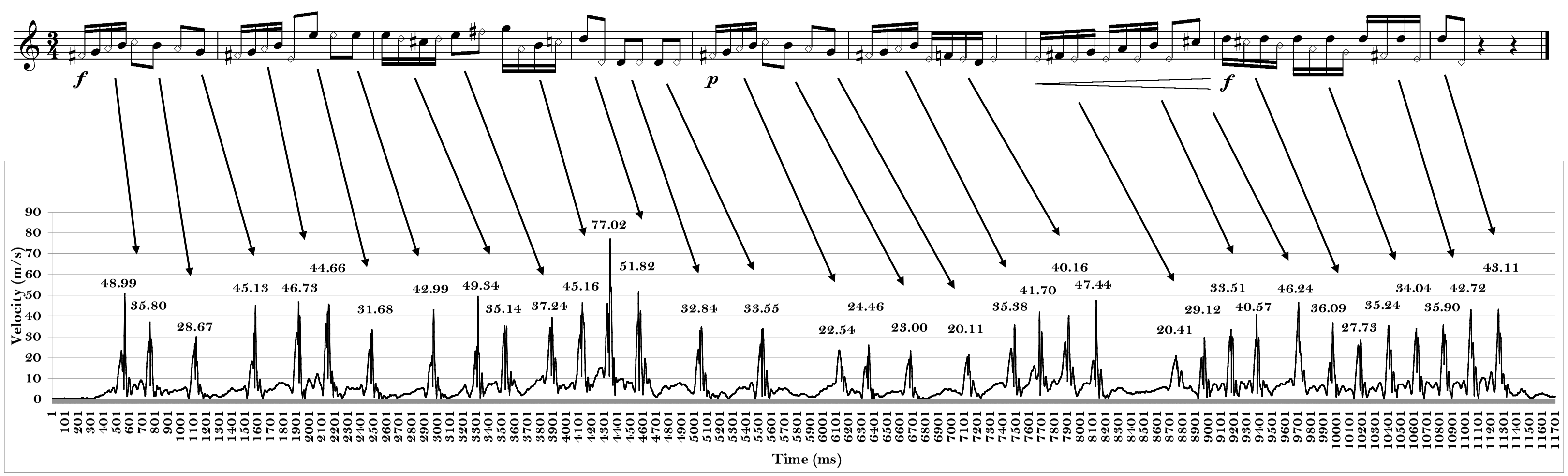
Figure 22: Pitch and Octave Identification



Right Hand Velocity Magnitude Measurements for *Keyboard Audition Book Etude #2*

Keyboard Audition Etude #2 consisted of 36 strokes executed with the right hand, and contained an average velocity magnitude of 37.95 m/s (85.00 mph). The velocity magnitude values, along with the corresponding musical notation for this excerpt are displayed in Figure 23. The use of solid note heads and hollow note heads were used to better aid in the reader's interpretation of the data as well as the use of arrows directing the reader from the musical notation to the corresponding velocity magnitude value. In Figure 23, the solid note heads notate the right hand strokes executed in this excerpt, and the hollow note heads notate the left hand strokes, of which data values were not measured in this particular portion of the study.

Figure 23: Right Hand Velocity Magnitude Values of *Keyboard Audition Etude #2* Excerpt with Musical Notation



During the first three full measures of the *Keyboard Audition Etude #2* excerpt, a moderate fluctuation in velocity magnitude values for the right hand were measured The velocity magnitude value fluctuation is likely a result of musical phrasing executed by the performer. A large increase in velocity magnitude, occurring during beat 3 of measure 23 at x-axis value 4201 ms, measuring 77.02 m/s (172.52 mph), is likely a result of a preparation for the large skip from d^5 down to d^4, occurring on the downbeat of measure 24. Evidence suggests that this skip, performed within a relatively brisk tempo requires a large amount of velocity in order to be performed at tempo, and may have affected the amount of velocity used slightly before this skip.

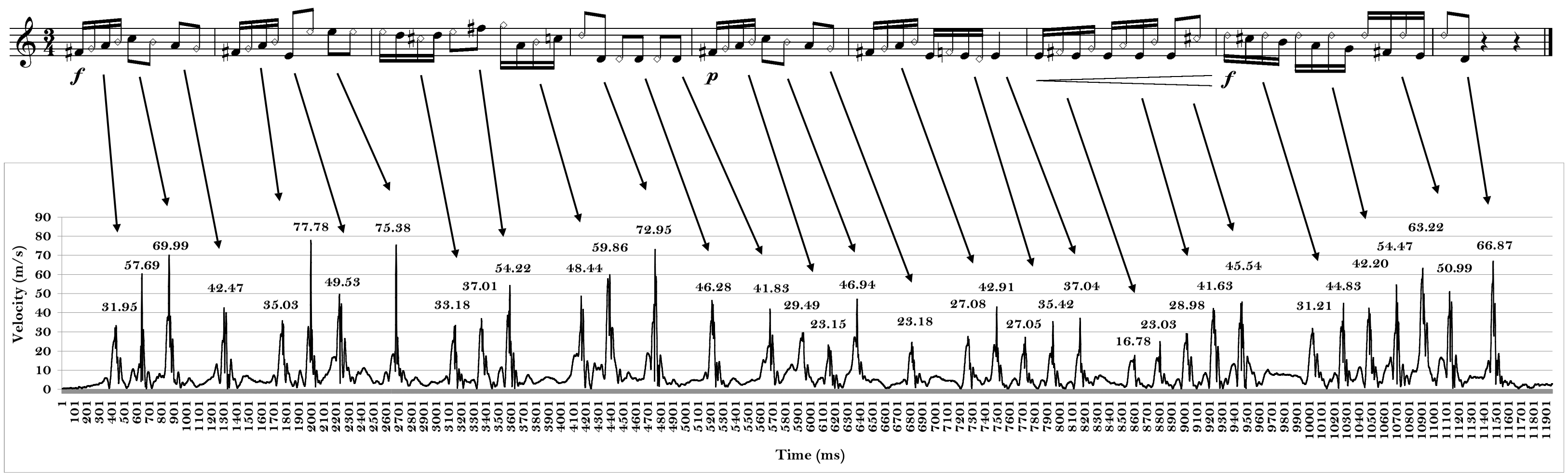
During measure 24 and 25, velocity magnitude values remained low, possibly because of the decreased dynamic level as compared to the previous measures. Collected data suggests lower dynamic levels may require an inherent lesser stroke velocity magnitude in order to be rhythmically executed correctly. This phenomenon is possibly supported by the notion that a short distance requires a slower speed of travel than a large distance when elapsed time of travel is of equal value. During the *Keyboard Audition Etude #2* excerpt, a soft dynamic level was executed with a low stick height, but time between individual pitches remained constant. In comparison to the louder portion, low velocity magnitude values were measured during this musical figure possibly due to a lack of required traveling distance in order to achieve the appropriate dynamical level.

Measure 27 contains a crescendo from a dynamic level of *piano* to *forte*, or soft to loud, and velocity magnitude values increased with little variation. Empirical data collected for this measure indicates velocity magnitude values and dynamic levels have a direct correlation when rhythm is constant, and movement horizontally from pitch to pitch is minimal. Although not present in the musical notation, a similar relationship is obvious in measure 28 but is likely a result of unintentional musical gesturing and phrasing.

Left Hand Velocity Magnitude Measurements for *Keyboard Audition Book Etude #2*

Figure 24 below contains left hand velocity magnitude values collected during the performance of *Keyboard Audition Etude #2*, and the appropriate musical notation is displayed. Solid note heads represent strokes executed with the left hand, of which velocity magnitude values were measured, and hollow note heads represent strokes executed with the right hand.

Figure 24: Left Hand Velocity Magnitude Values of *Keyboard Audition Etude #2* Excerpt with Musical Notation



During the performance of *Keyboard Audition Etude #2*, 37 strokes were executed with the left hand, and an average velocity magnitude value of 44.21 m/s (99.03 mph) was measured. Velocity magnitude values were sporadic in comparison to the right hand velocity values. Inherent musical gestures are obvious, like that of measure 21 where a slight crescendo likely took place during beat 1, and resulted in a higher velocity magnitude value occurring on beat 2, measuring 69.9 m/s (156.78 mph).

The second left hand stroke occurring in measure 22, beat 1 (a^5), reported a relatively high velocity magnitude value. This may be a result of an anticipation of the movement from a^5 to e^4, as one may expect a higher velocity value to occur during the second note of a large skip, similar to previously discussed data values for the right hand. Evidence suggests that high velocity magnitude values present during the first note of a large skip may be a result of an anticipation of a skip from one note to another, whereas a high velocity magnitude value present during the second note of a large skip may be a result of a large distance covered during the skip itself. In either situation, stroke velocity is affected when a large skip from one pitch to another is performed.

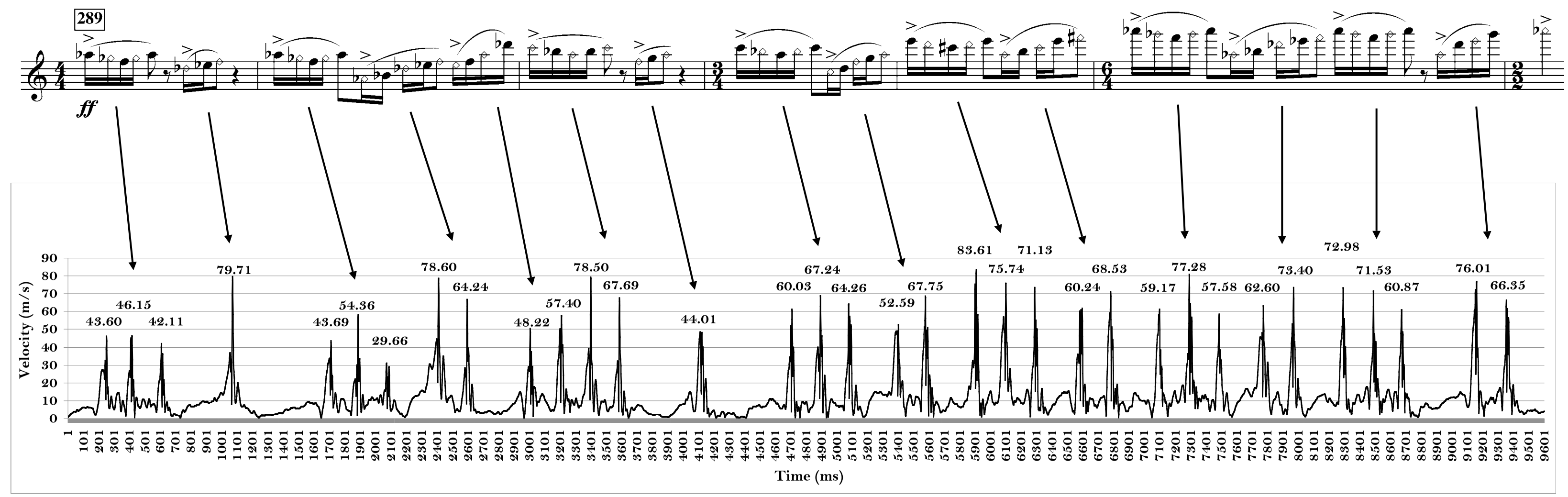
Measure 25 and 26 recorded a lower collection of velocity magnitude values occurring between x-axis values 5801 ms and 8101 ms. Reported low values, like that of the right hand measurements, are likely a result of an execution of a low dynamic level.

Empirical data suggests that low dynamic levels, when stroke motion is executed in relatively similar fashion, tend to yield low velocity magnitude values, and high dynamic levels tend to yield high velocity magnitude values respectively. This is very evident in measures 27, 28, and 29, as velocity magnitude values steadily increase as dynamic levels also increase during a notated crescendo, or during a crescendo that is a result of musical gesturing and phrasing.

Right Hand Velocity Magnitude Measurements for *Concerto No.1 for Marimba: Gate to Heaven*

The *Gate to Heaven* excerpt contained 34 right hand strokes yielding an average magnitude velocity value of 62.56 m/s (140.13 mph). Velocity magnitude values, along with the corresponding musical notation for this excerpt are displayed in Figure 25 below. As notated previously, solid note heads and hollow note heads were used to better aid in the reader's interpretation of data, as well as the use of arrows directing the reader from the musical notation to corresponding velocity magnitude value. In Figure 25, on the next page, solid note heads notate the right hand strokes executed in this excerpt, and hollow notes heads notate the left hand strokes.

Figure 25: Right Hand Velocity Magnitude Values of *Concerto No.1 for Marimba: Gate to Heaven* Excerpt with Musical Notation



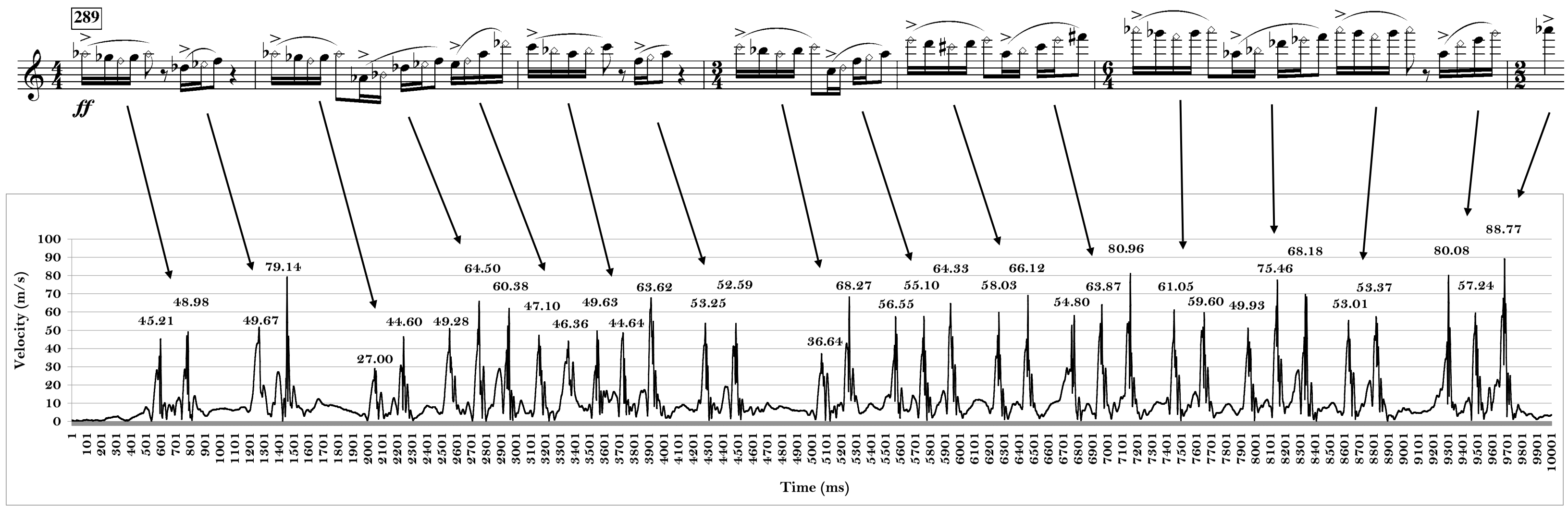
During the performance of the *Gate to Heaven* excerpt, the right hand measured a maximum velocity magnitude value of 83.61 m/s (187.29 mph) occurring at approximately 5901 ms. A minimum velocity magnitude value occurred at approximately 2101 ms, and measured 29.66 m/s (66.44 mph). Empirical data indicates a moderate amount of stroke velocity present in right hand strokes during measures 289 through 291 and includes a few high velocity magnitude values sporadically located throughout. An instance of high velocity magnitude occurs at approximately 1101 ms where stroke velocity measured 79.71 m/s (178.55 mph). Data indicates this instance of higher velocity magnitude is likely a result of a quick shift from E♭^{5} to A♭^{5} and a preparation for the accent occurring on the downbeat of measure 290. Of interest is a difference in velocity magnitude occurring on the first right hand stroke of measure 290, measuring 43.69 m/s (104.86 mph), and the second right hand stroke measuring 54.36 m/s (121.77 mph). Because of the increase in volume and need for accurate rhythm, empirical data suggests the first of these two strokes have a larger stroke velocity value because the stroke occurs at the beginning of the figure and contains a notated accent. Previous empirical data contradicts these measurements. This may be a result of motion from the sharp/flat manual to the natural manual, a shift from black to white keys on a piano, and an inherent need for increased stroke velocity in order for pitches to occur in a rhythmically accurate fashion. A similar occurrence of velocity magnitude values is present at the beginning of measure 291, measure 292, and twice in measure 294. Data collected indicates the shape of a small musical figure, similar to that of *Gate to Heaven*, may affect stroke velocity used to a greater extent than the execution of an accent.

The presence of low level velocity values occurring in between executed strokes appears in Figure 25. These low level values are maintained throughout the performance of the *Gate to Heaven* excerpt and measure between 10 and 15 m/s. This phenomenon may indicate a small amount of velocity is required to move horizontally from pitch to pitch, and may add to a total amount of velocity magnitude found in any given stroke. In addition, small velocity values seem to be elongated horizontally when more space occurs between consecutive stroke motions.

Left Hand Velocity Magnitude Measurements for *Concerto No.1 for Marimba: Gate to Heaven*

Figure 26 below displays data collected for the left hand while performing *Gate to Heaven*. Like that of previous figures, solid note heads represent strokes where velocity magnitude was measured, and hollow note heads represent strokes where data was not collected.

Figure 26: Left Hand Velocity Magnitude Values of *Concerto No.1 for Marimba: Gate to Heaven* Excerpt with Musical Notation



The performance of *Gate to Heaven* yielded 36 left hand strokes and an average velocity magnitude value of 57.70 m/s (129.25 mph). The average stroke velocity measured approximately 4.86 m/s less than the right hand average velocity values collected. A difference in average velocity magnitude value from one hand to another may be a result of the performer being right handed and inadvertently favoring the stronger hand.

At x-value 9701 ms a maximum velocity magnitude value of 88.77 m/s (198.85 mph) appears, and at x-value 2050 ms a minimum velocity magnitude value of 27.00 m/s (60.48 mph) occurs. Similar data discussed for the right hand is evident with the left hand. During measure 289, the repeated G$\flat^5$ contains similar velocity values respectively, a difference of 3.77 m/s (8.44 mph), whereas the same musical fragment occurring at the beginning of measure 290 contains a difference in velocity magnitude of 17.6 m/s (39.42 mph). Although this musical figure is exactly the same and should theoretically contain similar velocity values, an anticipation of the jump of an octave down from A$\flat^5$ to A$\flat^4$ may have affected the amount of velocity used.

Empirical data shows that an overall increase in velocity magnitude occurred throughout the *Gate to Heaven* excerpt culminating in the highest velocity magnitude value found within this study occurring during the last stroke executed. A large velocity magnitude value found within the last stroke of the *Gate to Heaven* excerpt may be a result of an inherent increase in musical tension as the pitch and key center progressively becomes higher, in addition to a cadence point occurring on the downbeat of measure 295. Data collected during this performance tends to support the idea that an increased dynamic level, combined with musical phrasing that purposely creates tension, may result in increased levels of velocity magnitude values.

CHAPTER VI

LIMITATIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Limitations

There are notable limitations to the present study. First, although data was collected in a consistent manner throughout the study, and stroke velocity was measured accurately given the equipment implemented, the placement of the accelerometer on top of the performer's hand measured stroke velocity in close proximity to the wrist, where stroke motion was initiated, and not at the head of the mallet where the largest amount of stroke velocity most likely occurred. Positioning the accelerometer on the marimba mallet head itself would have caused severe damage to the equipment, and likely rendered it unusable. While an attempt was made to ensure a consistent execution of grip, hand position, and stroke motion, small unintentional variations may have occurred. Bluetooth technology, such as that used in Fujinaga's study, would aid in eliminating possible damage to the equipment, and enable placement of the accelerometer inside the mallet head. In addition, using wireless equipment would enable the performer to execute the marimba excerpts without any physical impediment.

Second, collection of data points every one thousandth of one second diminished the amount of data able to be collected at one instance. This resulted in the need to select short marimba excerpts to avoid potential loss of data. Access to a more sophisticated data collection software may enable a larger amount of collectable data to be captured at one time without diminishing the frequency of data collection per second. In addition to the short length of time that the software was able to capture data, the treatment of data, converting acceleration values to velocity magnitude values, is somewhat laborious. This significantly limits the practical application of data collection equipment within a pedagogical environment.

Third, the current study was treated as a pilot study, solely designed to answer the question of whether stroke velocity used in two-mallet marimba performance could be quantified using the prescribed methodology. The use of stroke velocity during the execution of a preparation stroke, resurrection stroke, and the academic stroke is subjective, and the velocity magnitude values measured in comparison to the low velocity piston stroke and high velocity piston stroke may be unintentionally skewed. As stated in Chapter 5, stroke velocity, when executed by an experienced performer, is subject to change. The preparation stroke, the resurrection stroke, and the academic stroke could have been executed with an extreme minimal amount of stroke velocity, or an extreme high amount of stroke velocity. The amount of stroke velocity used in this study was a result of a focused path of travel true to the variations of a correctly executed piston stroke and the use of a stroke velocity most comfortable to the performer at the time of data collection.

Implications for Future Research

Because of the nature of this study, a multitude of implications for future research are possible. An obvious follow-up to this study would aim at determining the relationship between sound quality and stroke velocity. This may be explored using the same equipment and methodology of this study while including a number of percussionists performing the same marimba excerpt, and should include access to more sophisticated data collection equipment A panel of educators and professional musicians could then determine the quality of sound achieved using a rubric designed to aid in this process. A panel of educators and professional musicians would best serve this type of study because of the relative subjectivity of sound quality found in percussion performance.

In addition to determining a relationship between sound quality and stroke velocity, an acoustical relationship between stroke velocity and marimba bar resonance may serve as a useful extension of this study. Using audio recording software to measure the length of marimba bar resonance when varying degrees of stroke velocity are executed would determine to what extent stroke velocity affects the timbre achieved by a percussionist. In many instances, an obvious difference in timbre and resonance is noticeable when an excessive amount of stroke velocity is used during a performance. The ability to quantify this aural difference would be of significant value to a percussionist and to percussion instrument manufacturers.

Similar to determining a relationship between acoustics and stroke velocity, the extent to which a marimba bar bends downward during a stroke in relationship to stroke velocity could be of particular interest to marimba manufacturers and percussionists alike. Determining if a relationship exists between the amount of stroke velocity found within a stroke, and whether or not velocity affects the shape the marimba bar takes during it being struck by a mallet may determine more specific causes in timbre change when velocity is altered.

Pedagogically, this study may lead to a design method in aiding beginner percussionists to learn how to vary the amount of stroke velocity used in percussion performance, ultimately enabling the student to alter velocity to a greater extent in a shorter amount of practice time. In many instances, beginner percussionists, if not taught properly from the onset of private or group lessons, develop a habit of playing with a large amount of stroke velocity to achieve sound. This significantly hinders a student's ability to perform with less exertion of energy, perform with a relaxed physical approach to the instrument, and to manipulate the sticks or mallets effectively during moderate to advanced level literature performance. With significant changes to simplify the conversion of data from acceleration values to velocity values, access to more sophisticated data collection equipment, and the use of real-time data capturing, the measuring of a student's stroke velocity used during a performance may provide instant feedback for the student to better enable he or she to minimize stroke velocity when necessary or desired.

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